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NRL/MR/6380--95-7424

Computational Modeling of Coating Integrity Effects on Impressed Current Cathodic Protection System

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March 28, 1995

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 28, 1995	Final Aug 1993 - Dec 1994

4. TITLE AND SUBTITLE

Computational Modeling of Coating Integrity Effects on Impressed Current Cathodic Protection System

5. FUNDING NUMBERS

PE-62234N, RS34S57

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
Washington, DC 20375-5320

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/MR/6380--95-7424

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Carderock Division
Naval Surface Warfare Center
Bethesda, MD

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

*George Washington University

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Coatings are often used in conjunction with impressed current cathodic protection (ICCP) systems to minimize the effect of corrosion on marine structures. The presence of a coating reduces the current required by an ICCP system. The integrity and efficiency of the coating determines the level of current reduction achieved over the bare metal condition. One of the difficulties is designing a combined coating and ICCP system is that coatings deteriorate with time in service due to a variety of factors including mechanical wear and organic attack. In this study computational modeling is used to determine the variation in current demand required for corrosion protection for increased levels of damage to the protective coating applied to the propellers of a surface ship.

14. SUBJECT TERMS

Cathodic protection
Boundary element
Computational simulation

15. NUMBER OF PAGES

16

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

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COMPUTATIONAL MODELING OF COATING INTEGRITY EFFECTS ON IMPRESSED CURRENT CATHODIC PROTECTION

ADMINSTRATIVE INFORMATION

This report was prepared as part of the Ship and Submarine Materials Technology Program sponsored by ONR 332 (Dr. Lewis Sloter). Mr. Ivan Caplan of the Carderock Division, Naval Service Warfare Center (CDNSWC Code 0115) is the CDNSWC Technology Area Manager for this program. This effort was performed by the Mechanics of Materials Branch, Naval Research Laboratory, Code 6380 under Program Element 62234N, Structural Alloys Project RS34S57.

INTRODUCTION

Coatings are often used in conjunction with impressed current cathodic protection (ICCP) systems to minimize the effect of corrosion on marine structures. The presence of a coating reduces the current required by an ICCP system. The integrity and efficiency of the coating determines the level of current reduction achieved over the bare metal condition. One of the difficulties in designing a combined coating and ICCP system is that coatings deteriorate with time in service due to a variety of factors including mechanical wear and organic attack. The extent and rate of coating deterioration is often only known as a result of inspections performed after the structure has been removed from service. One approach for system design ignores the existence of the coating in the design of the companion ICCP system. In this way the ICCP system is designed for the worse case condition. That is, the ICCP system is designed to provide corrosion protection in the event of complete coating failure. However, coating damage may only be minor and the operating parameters defined by the worse case design analysis may not be appropriate for actual operating conditions. In such cases, the actual variation in operating parameters required by a steady decrease in coating efficiency would be of interest to the designer. This information could be incorporated into the choice of power supplies and other details of the ICCP system design.

Computational modeling has become an established design tool in structural engineering and other disciplines. Efforts have been made to establish computational modeling of electrochemical corrosion systems as an accepted design and diagnostic methodology. Computational techniques, with emphasis on finite element and boundary element methods, and their application to corrosion systems are summarized in review articles by Zamani et al [1] and Munn [2]. The requirements of an accurate electrochemical corrosion computational study are presented by DeGiorgi and Kaznoff [3]. The purpose of this study is to demonstrate the capability and versatility of computational modeling by determining current demand required for corrosion protection for increased levels of damage to the protective coating applied to the propellers of a surface ship.

Manuscript approved February 2, 1995.

SCOPE OF WORK

The propellers are a major feature of a surface ship which require corrosion protection. Protective coatings applied to the propellers may or may not provide complete protection during the entire service life of the ship. A computational study is undertaken to examine the effect varying degrees of damage to the propellor coating has on the current demand for an ICCP system. The ICCP system studied is an existing system installed on a U. S. Navy destroyer. Reduced coating efficiency is used to incorporate the effects of coating damage into a computational model. It is assumed that a perfect ground exists between the ICCP system and the propellers. The damage configuration considered is based on that of a new, or freshly painted, ship, i.e. exposed steel representing the docking blocks combined with varying level of damage to the propellers. The levels of damage to the propellers included in the analysis vary from zero to 10% of the propellor surface area. The case of totally bare propeller, 100% damage, is also included in the study to validate the model by comparison with experimental results and to provide an upper bound solution for current demand. Dynamic, or ship under way, conditions are examined.

MATHEMATICAL FORMULATION

The determination of the electrochemical response of the structure and it's associated ICCP system require the solution of LaPlace's equation.

$$\frac{\partial^2\Phi}{\partial x^2} + \frac{\partial^2\Phi}{\partial y^2} + \frac{\partial^2\Phi}{\partial z^2} = 0$$

The relationship between the electrical potential, Φ, and current density is determined from the solution of LaPlace's equation combined with the appropriate material response and boundary conditions. A constant value of conductivity for the seawater surrounding the surface ship is assumed in the mathematical formulation.

Electrical current sources, such as the ICCP system anodes, are defined by:

$$i = \frac{\partial\Phi}{\partial n} = C_2$$

where n is the normal to the boundary and C_2 is a constant.

Coated surfaces without any damage are defined as:

$$i = \frac{\partial \Phi}{\partial n} = 0$$

The intact coating is modeled as an insulator which allows no transfer of electrical current.

The electrical current density on an exposed metal surface is determined from the material polarization response and the measured electrical potential on the metal surface:

$$i = f(\Phi)$$

where f represents a functional relationship. In this analysis the functional relationship is defined by a non-linear experimental polarization curve. The non-linear polarization response is modeled as a series of linear segments for input to the commercial boundary element code.

SHIP GEOMETRY

A schematic of the ship hull and ICCP system analyzed are shown in Figure 1. The ship has dual rudders and propellers. The ICCP system analyzed consists of 3 pairs of symmetrically placed anodes and a centerline anode in the aft section of the hull, two power supplies and two reference cells. The reference cells are control points for the ICCP system. Power input is based on voltage readings at the reference cells. Reference cells are located as shown on Figure 1. The fore and mid-section anodes are connected to a single power supply and use the forward placed reference cell. The remaining anodes are connected to a separate power supply. ICCP system symmetry and geometric symmetry of the hull allow for half of the ship to be modeled. The section of hull modeled is that which is below the design waterline.

COMPUTATIONAL MODEL

In the evaluation of the cathodic protection systems using boundary element methods the boundary dividing the structure from the electrolyte is modeled. In the case of a structure surrounded by a nearly infinite medium, such as a surface ship surrounded by the open sea, the inner boundary is the ship hull and the outer boundary of the computer model is an artificial boundary placed a large distance away from the structure. This creates a large but finite domain for the solution of LaPlace's equation.

The boundary element model created for the analysis is shown in Figure 2. The model consists of 1596 hybrid quadratic elements fabricated of 6916 mesh points. The hybrid quadratic elements are

standard elements in the commercial code used. The hybrid elements used have a linear representation of the unknown variables, in this case electrical potential and current density, and a quadratic geometric representation. These elements offer good convergence characteristics, allow for easier modeling of curved surfaces while maintaining the lower number of degrees of freedom associated with linear elements. A solution of the boundary element model requires slightly more than 2 hours of computer processing time on a CRAY-YMP supercomputer. This boundary element mesh had been previously validated by comparison with experimental results [4]. The boundary element model developed is a detailed modeling of the curvature of the hull surface, has geometrically distinct modeling of the rudders and geometrically distinct modeling of the propellers.

The impressed current anodes are explicitly included in the boundary element model. The source anodes have finite areas and fixed locations. Anodes connected to the same zone are prescribed identical voltages as part of the defined boundary conditions.

To incorporate the effects of coating damage in computational modeling, holidays in the coating must be included in the model. Holidays can be modeled either as an effective reduction in the efficiency of the coating or as discrete breaks in the coating exposing the base metal to the electrolyte. In cathodic protection system design, holidays are not typically modeled as discrete defects but rather are modeled as a reduction in the coating effectiveness. In the coating effectiveness approach, a 90% coating efficiency corresponds to 10% exposed metal and the current required to protect an area is defined as 10% of the current needed to protect the same area if it was totally bare metal. In this analysis, the coating damage on the propellers is modeled by the effective coating efficiency approach.

Three materials were incorporated into the boundary element model; steel, nickel-aluminum-bronze (NAB) and a corrosion preventative coating were used to model separate specific regions of the ship. The hull is assumed to be undamaged coating. All surfaces are assumed to be free of calcareous deposits. NAB material properties are modified to account for the effective coating efficiency for the levels of damage examined. There are no aging effects associated with time in service incorporated in the analysis. The polarization response of steel and NAB is as determined in large scale testing in which instrumented metal plates were towed in natural seawater [5]. The polarization response was determined for the materials of interest at the appropriate towing speed to represent dynamic, or ship under way, conditions.

The infinite seawater domain is approximated by a box of elements which surrounds the ship model. The box elements are defined with a current density of zero to approximate the correct boundary conditions at infinity. The surrounding seawater is modeled with a constant resistivity of 20 Ohms-cm.

The total current supplied to each zone is calculated from the boundary element computational results. In this analysis, each power zone is defined as being powered by a external power supply which is sufficient for the current demands.

COMPUTATIONAL ANALYSIS

A commercial boundary element program [6] was used to solve the LaPlace governing equations for the defined ship structure. The boundary element analysis uses defined voltage values at the impressed current anodes, defined current density on the box defining infinity, and material polarization characterization to solve LaPlace's equation and determine the voltage and current density at all points on the ship hull model.

The boundary element code uses an iterative solution procedure to solve LaPlace's equation when nonlinear polarization boundary conditions are used to describe material behavior. A valid solution must satisfy three independent mathematical criteria:

(1) the potential satisfies the LaPlace equation throughout the electrolyte domain.

(2) the flux balance is satisfied (the current entering the electrolyte is equal to the current leaving the electrolyte).

(3) the potential and current density results fall on the given polarization curve for each nonlinear material type for each element.

A maximum solution tolerance of 1.0% was used in the present study.

In addition to the mathematical convergence criteria, the solution of interest must result in a potential of 0.85 Volts Ag/AgCl at the reference cell locations. This corresponds to the desired operating conditions of the shipboard system.

The baseline condition examined corresponds to a freshly painted ship at the beginning of it's service life. The only portion of the ship which is not protected by an intact perfect coating are docking blocks which are bare steel. The docking blocks represent 1% of the total underwater hull surface area. The surface area of the propellers is 2% of the total underwater hull surface area. The effects of coating damage is simulated by analysis of five coating damage levels ranging from no coating damage to a completely bare propellor. Intermediate levels of coating damage considered were 1%, 5% and 10% of the propellers' surface area. An effective coating efficiency approach was taken in modeling the current demand of the damaged propellor. Recent work by Kennelley, Bone and Orazem [7,8] indicate that this assumption of a uniform reduced coating efficiency is appropriate only when holidays are very small. Therefore, coating damage was limited to 10% of the surface area since it may not be appropriate to model higher percentages of damage as uniformly distributed small holidays. It was felt that 10% damage could be reasonably modeled as uniformly spaced small areas of damage over the entire propeller surface.

The bare propellor case was compared with experimental results as part of the validation study for the computational model [4]. The results of minimum damage dynamic condition case are reproduced here as an upper bound on the current requirement of the ICCP system as designed. Physical scale model experimental data does not exist for any of the other propeller coating configurations considered in this analysis. A comparison of experimental and computational current requirements are shown in Tables 1 and 2. The potential profile along the ship centerline and along the hull at a depth of 10 feet from the waterline are shown in Figure 3. Physical scale modeling, in which the geometric dimensions and the electrolyte conductivity are scaled, was used to experimentally simulate the shipboard ICCP system. Physical scale modeling has been verified by comparison with full scale ship data obtained during sea trails [9,10]. As can be verified by an

examination of Tables 1 and 2 as well as Figure 3, the boundary element model yields accurate results for the minimum damage dynamic condition case.

COMPUTATIONAL RESULTS

Results examined for this evaluation include the current demand required to maintain the reference cells at 0.85 Volts Ag/AgCl and the potential profiles at the ship centerline and along the ship hull at a depth of 10 feet below the waterline. The voltage along the lower surface of the rudder and at the lower tip of the propellers are also examined. Protection from corrosion is defined as corresponding to a voltage of 0.85 Volts Ag/AgCl. For this analysis, no maximum level of voltage is prescribed as a design limit.

The total current required for achieving a reference cell reading of 0.85 Volts Ag/AgCl is presented in Tables 3 and 4. The amount of current necessary increases with increasing levels of damage to the propellor coating. As can be seen from the data presented in Tables 3 and 4, the increase in current is shared by both forward and aft systems. This indicates that even though the increase in damage is concentrated in the aft section, the system responds globally and both forward and aft power sources are affected.

The potential profile along the centerline of the ship hull and along the ship hull at a depth of 10 feet are shown in Figure 4 for the extreme damage conditions of a perfect coating and completely bare propellers. The other damage conditions are bounded by these extreme cases. The potential profiles for all damage conditions are similar.

The level of corrosion protection provided to the rudder is affected by the level of damage to the propellor coating. The rudder, as represented by the lower surface of the rudder, has potentials above the target value of 0.85 Volts Ag/AgCl for zero to 5% propellor coating damage. At 10% propellor coating damage the potential readings fall below the target potential as shown in Table 5. The value of 0.81 Volts Ag/AgCl for a bare propellor compares favorably with a value of 0.83 Volts Ag/AgCl reported for this same region for physical scale modeling experiments.

The level of corrosion protection to the propellor is affected by the amount of damage to the propellor coating. The propellor coating damage is modeled as uniformly distributed small holidays which are distributed over the entire surface area of the propellers. Results from this analysis are only appropriate when the damage mechanism is such that this is a realistic model of the coating damage. A trend of decreasing potential with increasing damage is shown in Table 6. In the extreme case of completely bare NAB propellers, the potential reading at the lower tip of the propellor is 0.68 Volts Ag/AgCl compares favorably to a reading of 0.71 Volts Ag/AgCl for this same region from physical scale model experiments.

CONCLUSIONS

The power requirements for corrosion protection using an existing ICCP system for intermediate levels of propellor coating damage has been determined using boundary element techniques. The

boundary element model and associated polarization curves used in the present analysis were verified by comparison with physical scale model experimental results. Propellor coating damage is modeled as small holidays uniformly distributed over the surface of the propellor. In cases of larger amounts of damage a different modeling technique may be required for accurate representative of the coating damage.

The computational modeling approach clearly allows the designer to interrogate different damage conditions which may occur during the life of the structure in order to better define the system operating requirements. The repetition of physical scale model experiments at these intermediate damage conditions would be expensive in terms of time, resources and finances. This analysis shows the versatility of computational modeling when applied as a design tool. Multiple damage configurations are modeled quickly and with a high level of accuracy based on the verification of the model and procedure for worse case conditions.

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Table 1
Current Comparison - Bare Propellor Condition
Amps

	Experimental	Computer Results
Forward System	25.8	22.3
Aft System	39.1	41.8
Total	64.9	64.0

Table 2
Current Comparison by Component - Bare Propellor Condition

Amps

	Experimental	Computer Results
Docking Blocks	14.1	13.7
Propellor	44.5	50.3

Table 3
Current Requirement
Amps

	Percent Damage to Propellor Coating				
	0.	1.	5.	10.	100.
Forward System	4.2	4.4	5.0	5.7	22.3
Aft System	10.8	11.0	11.8	12.6	50.3
Total	15.0	15.4	16.8	18.4	64.0

Table 4
Current Requirement by Component for Damaged Paint
Amps

	Percent Damage to Propellor Coating				
	0.	1.	5.	10.	100.
Docking Blocks	15.0	13.5	12.4	11.0	13.7
Propellers	-0-	1.9	4.4	7.4	50.3

Table 5
Potential at Lower Surface of the Rudders
Volts Ag/AgCl

	Percent Damage to Propellor Coating				
	0.	1.	5.	10.	100.
Computer Results	0.89	0.89	0.86	0.82	0.81
Experimental	--	--	--	--	0.83

Table 6
Potential at Lower Tip of Propellers
Volts Ag/AgCl

	Percent Damage to Propellor Coating				
	0.	1.	5.	10.	100.
Computer Results	0.89	0.88	0.85	0.81	0.68
Experimental	--	--	--	--	0.71

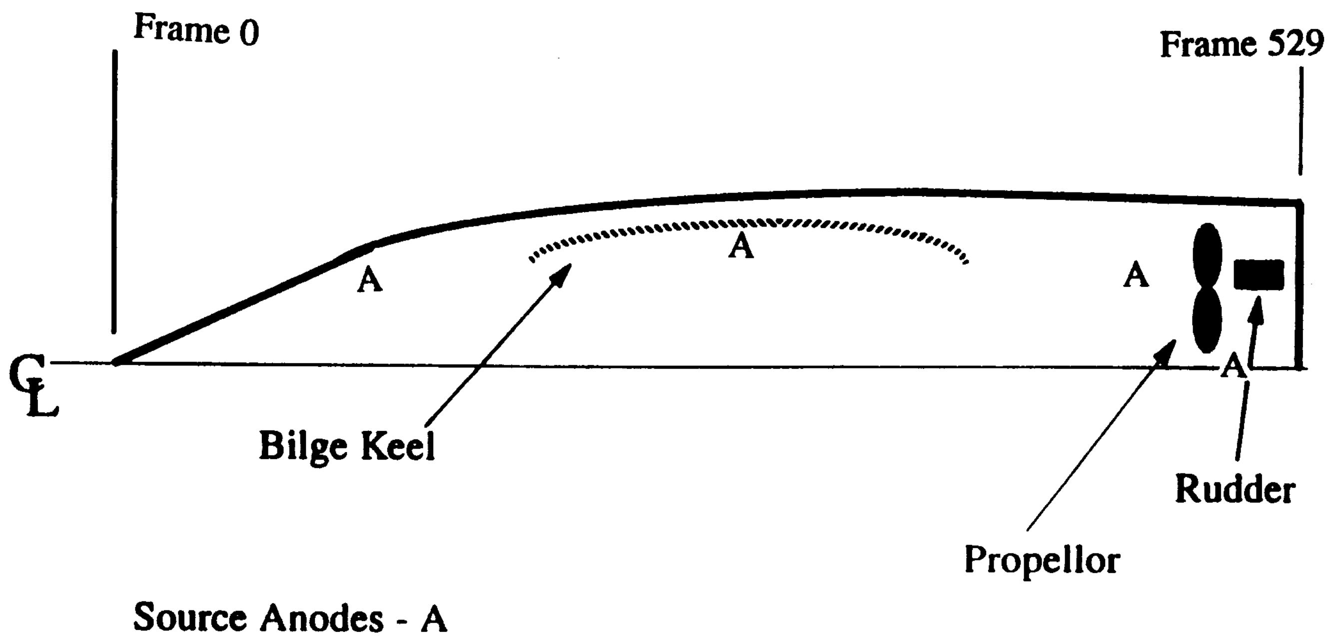

Fig. 1 Schematic of Ship Hull and ICCP System

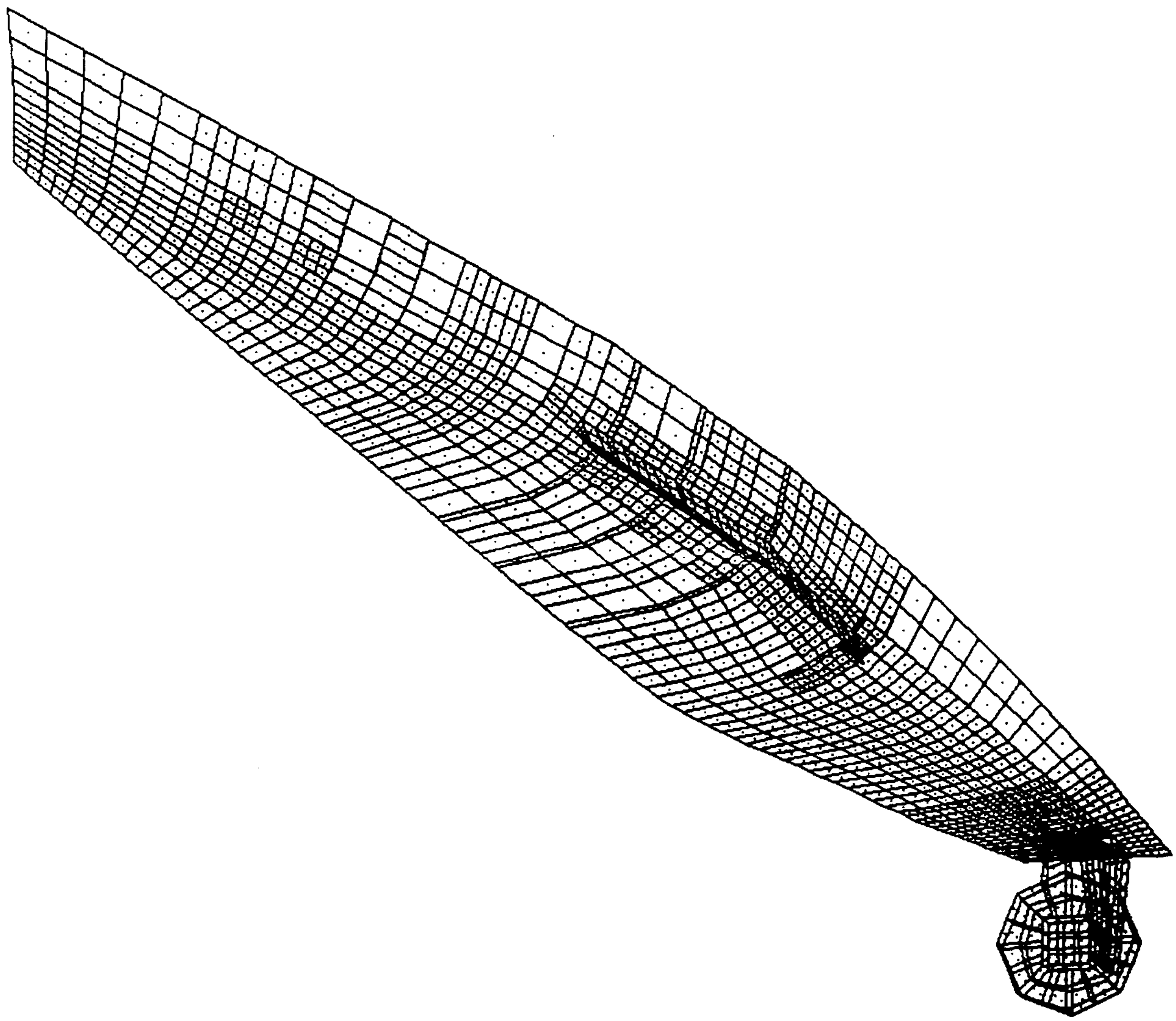

Fig. 2 Boundary Element Mesh

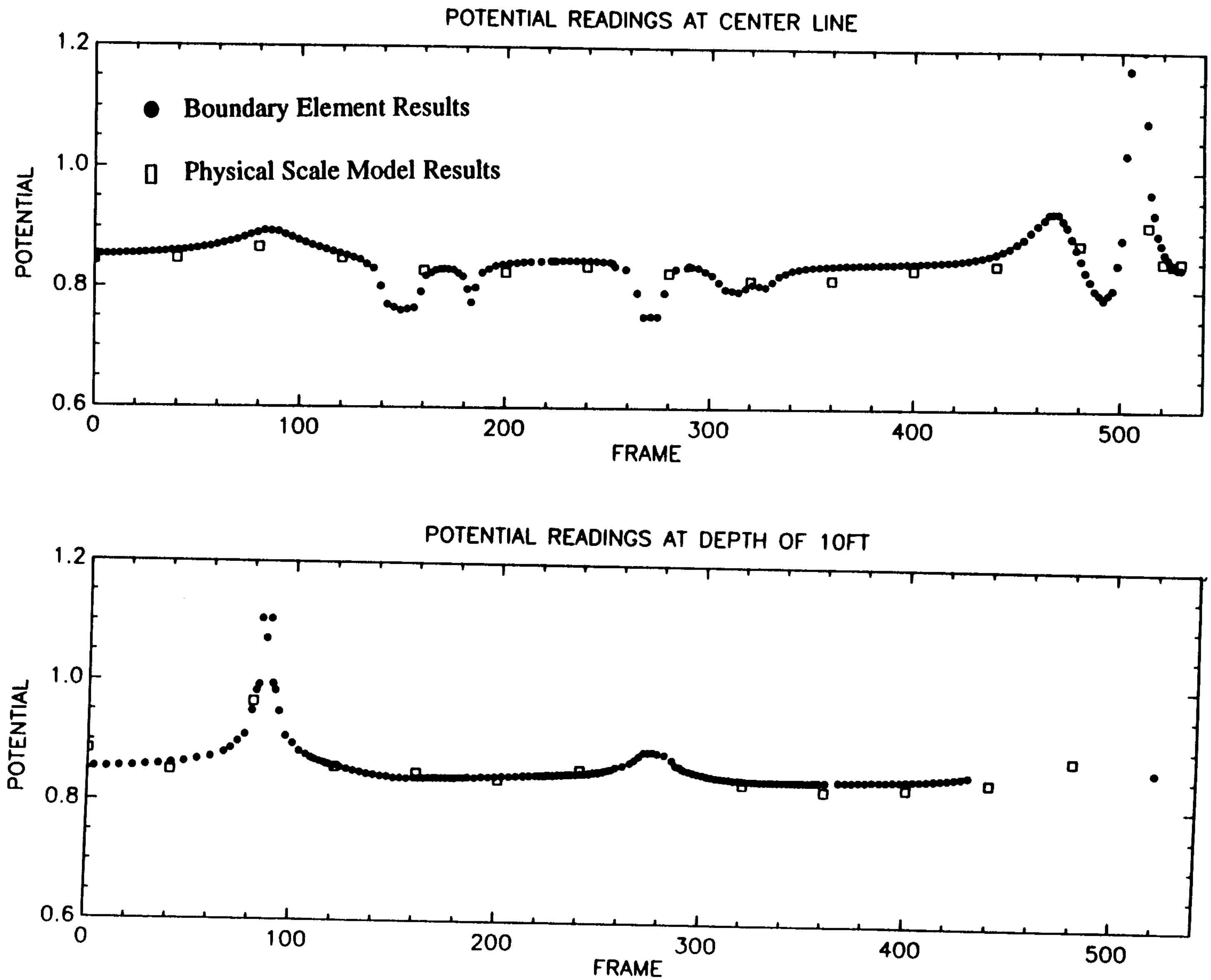

Fig. 3 Physical Scale Model and Computational Potential Profiles

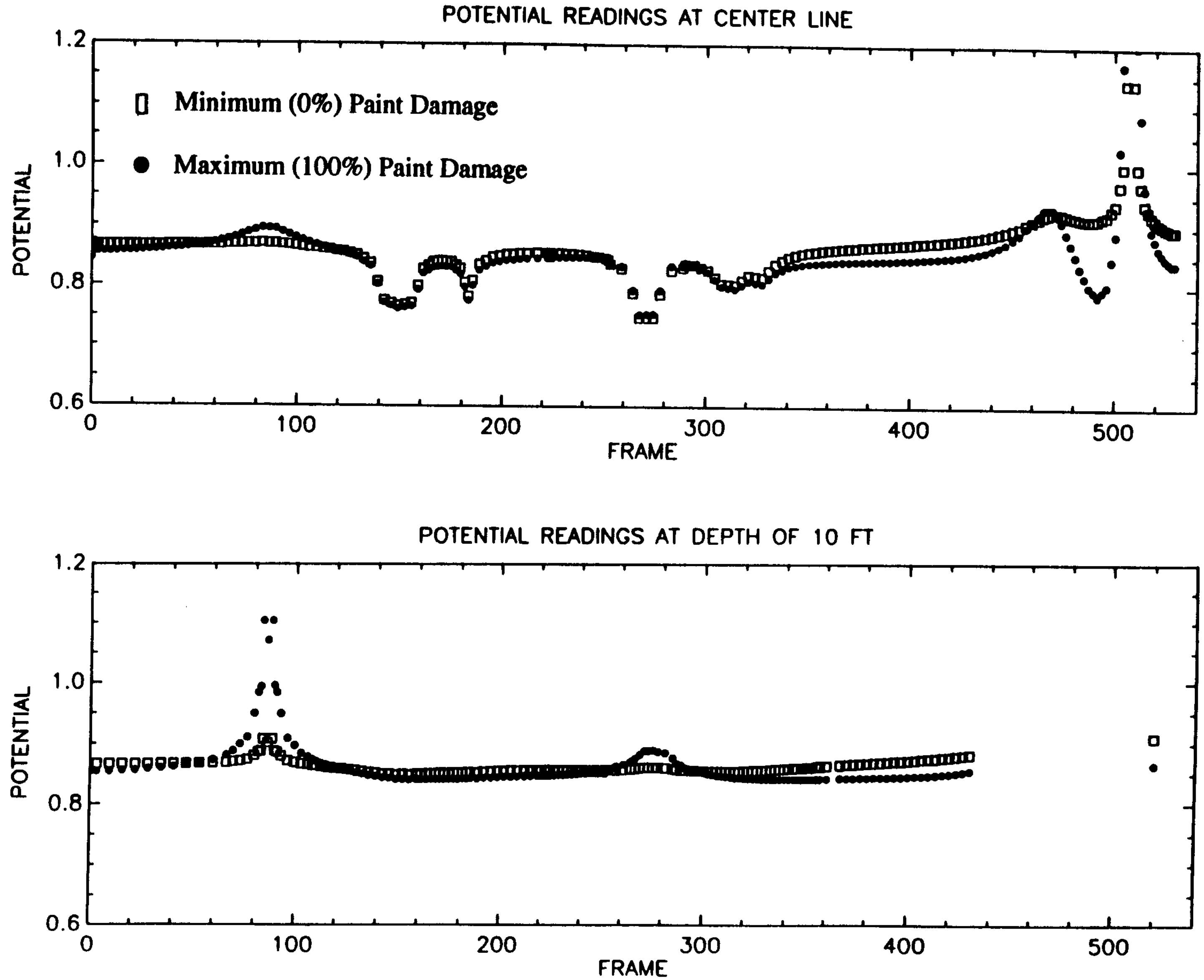

Fig. 4 Potential Profiles for Minimum and Maximum Damage